Center for Plasma Material Interactions

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Plasma Cleaning of Nanoparticles from EUV Mask Materials

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Introduction

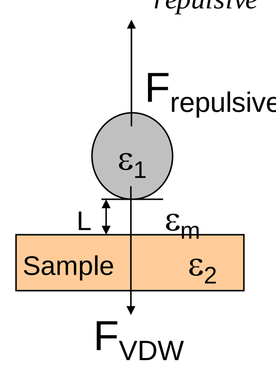
Nanometer scale contamination has proven to be a difficult obstacle to overcome in terms of surface cleanliness in EUV lithography. Plasma-Assisted Cleaning by Electrostatics (PACE) works by utilizing a pulsed plasma as well as a pulsed DC substrate bias to charge particles and then repel them electrostatically from the surface. The particles are then pumped out of the system. Removal of this nature is a dry cleaning method and removes contamination perpendicular from the surface instead of rolling or sweeping the particles off the surface, a benefit when cleaning patterned surfaces where contamination can be rolled or trapped between features. Also, an entire mask can be cleaned at once since the plasma can cover the entire surface, thus there is no need to focus in on an area to clean. PACE has shown greater than 90% particle removal efficiencies (PRE) for 30 – 220 nm PSL particles on ruthenium capped quartz. Removal results for silicon surfaces and quartz surfaces show similar removal efficiencies. Results showing conclusive before and after images of cleaning 30 nm, 80 nm, and 220 nm nanoparticles from samples of interest to EUV lithography are presented as well as damage assessments.

The ability to maintain a defect free surface is a critical issue still facing the progression of EUVL into mainstream production. Of those surfaces, the mask may be the most important part due to pattern transfer errors being a major limiting factor for throughput and the overall cost of ownership of an EUV tool. With a quick and dry cleaning technique, a mask can undergo repeated cleaning without the need for a wet chemistry removal step, saving time and maintaining the integrity of the surface

Particle Adhesion Theory

Force balance on the particle

$$\sum F = 0 = F_{repulsive} - F_{VDW}$$



F_{vdw} is in the range of 10^{-12} to 10^{-9} Newtons

In order to remove particles, we need to provide enough electrostatic force in order to overcome F_{VDW}.

Particle Charging Determination

$$U = \frac{(q_e)\, q_p}{4\pi\varepsilon_0 r_p} + \left|(q_e)\Delta V\right|$$

The removal force is dependent on two factors, the electric field and the charge of the particle. To find the maximum charge of a particle, q_p, one can solve an energy balance

$$E_{child} = \frac{4}{3}\frac{V}{s_{child}}\left(\frac{X}{s_{child}}\right)^{\frac{1}{3}} = 3.3\,x\,10^5\,\frac{volts}{meter}$$

← A typical plasma sheath (Child Law Sheath Model), s_{child} is the sheath width.

X is the distance into the sheath as measured from the sheath/pre-sheath boundary

$$E_{matrix} = \frac{q \cdot n_i}{\varepsilon_0} X = 1.2\,x\,10^6\,\frac{volts}{meter}$$

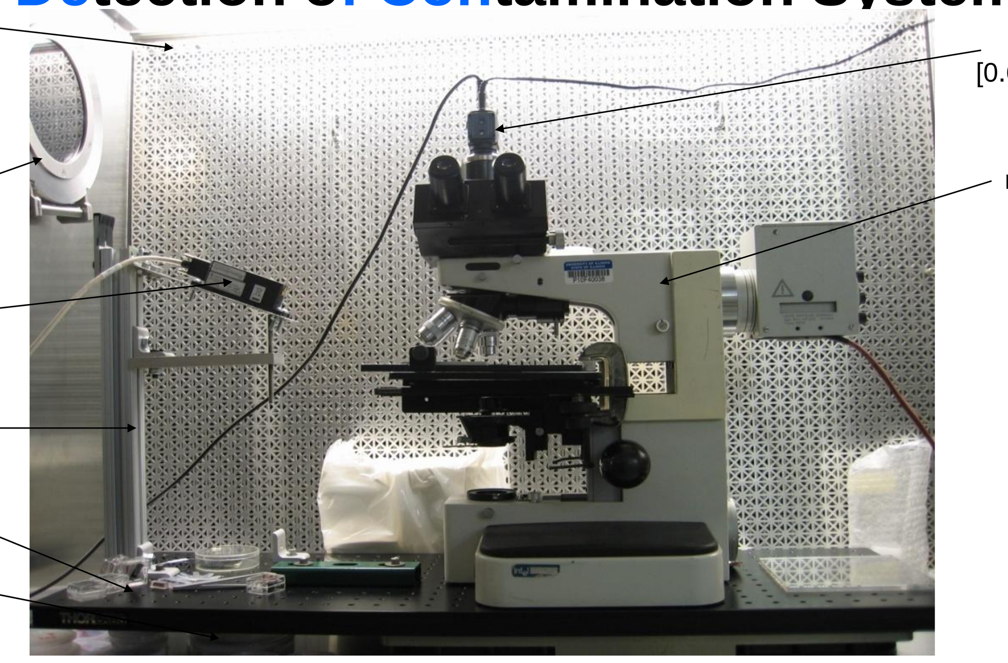
← A large negative bias sheath (matrix sheath model), n_i is the ion density of the plasma.

$$\Gamma_e = \frac{1}{4} n_e(U') v_{U'} \exp\left[\frac{\frac{-e q_p(t)}{4\pi\varepsilon_0 r_p}}{k_B T_{U'}}\right]$$

The charging time for a particle can be determined by calculating the electron flux to the charging particle.

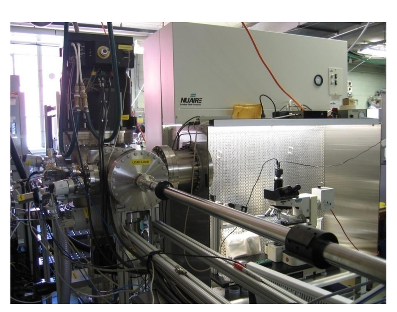
For a 30 nm spherical particle, the charging time is 1.7 μs to obtain a theoretical charge maximum of 175 excess electrons.

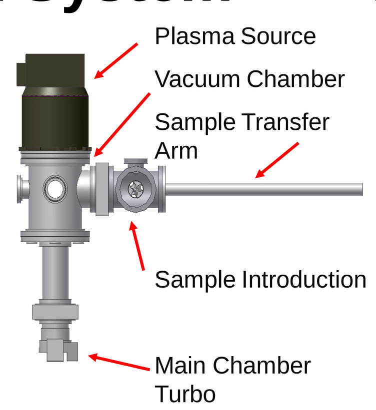
A new inspection tool was built for PACE sample analysis at the University of Illinois: The Detection of Contamination System



The DEFCON system is located in a class 100 laminar flow hood directly attached to the PACE chamber so that samples can be analyzed before and after PACE processing without being transferred through a "contaminated" environment.

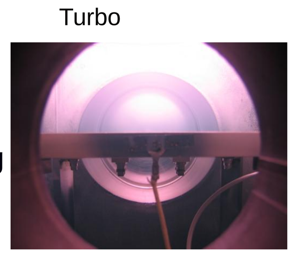
The PACE System





←PACE helicon plasma source

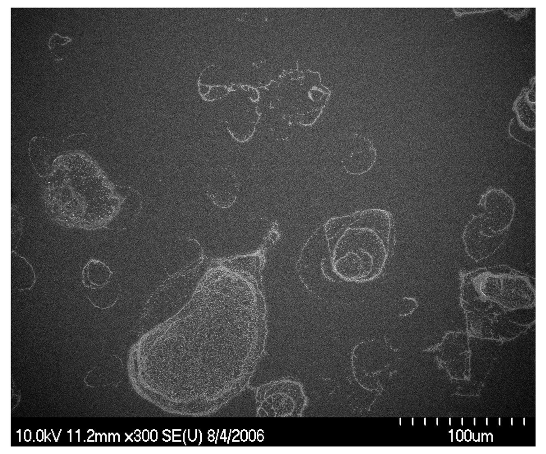
Plasma interacting with the PACE sample holder →



PACE experiments including sample preparation, imaging, and processing occur in approximately 30 minutes

Previous Removal Results

(comparison between processed and control samples)



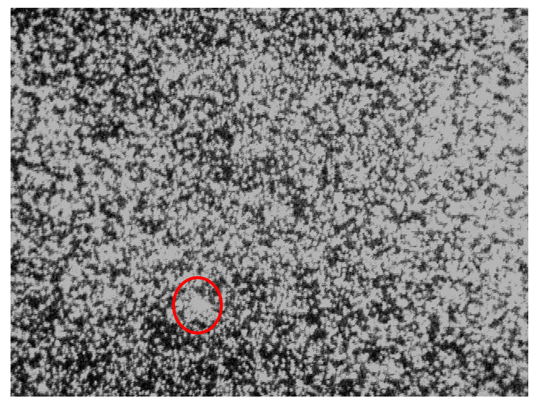
Sample Material	PRE (30nm, 80 nm, 220 nm PSL)
Silicon (wafer)	82.5 %
Quartz (1/4" thick)	73 %
Ru capped quartz (2.5nm Ru/100nm Si/quartz)	90 %

Control Sample 1.5% 0.8% covered   Processed Sample 0. 16% 0.007% covered

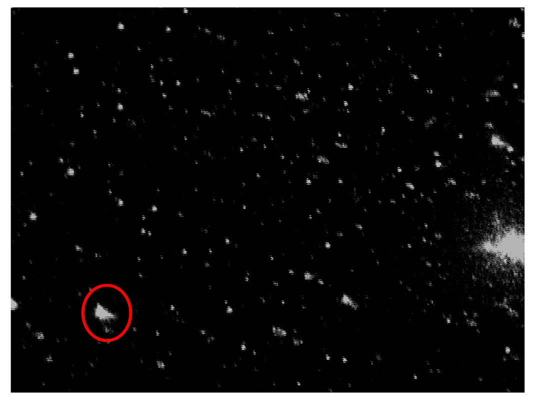
After 10 minutes of cleaning, we have a particle coverage **reduction of 90 %**

Cleaning may be much better – dust from not being in a clean room is also counted !

Removal Results of 80 nm PSL's From Si



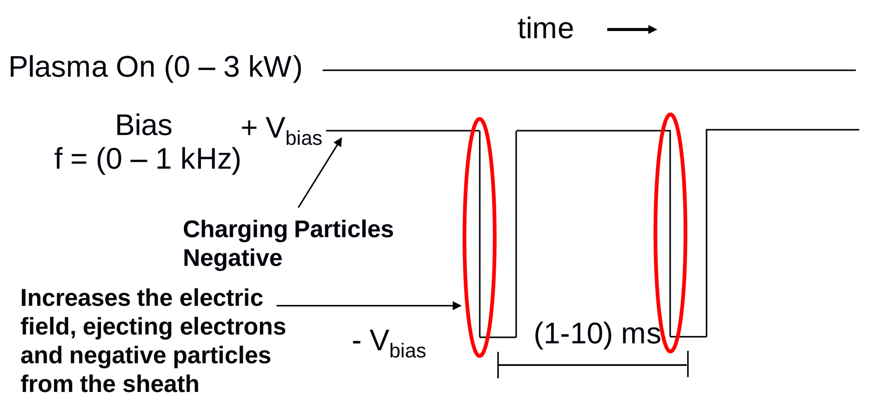
DEFCON image before



DEFCON image after

These 80 nm PSL's were deposited by an outside source on a 1 inch silicon wafer. The sample was processed in the PACE chamber using optimized plasma and pulsing parameters. **PRE = 94%**

How Does PACE Work ?



- During the positive portion of the pulse, electrons are drawn out of the plasma to the sample surface, striking both the particle as well as the surface. Electrons that hit the particle add to charging, and those that hit the sample are conducted away into the power supply.
- During the negative portion of the pulse, the sheath potential is suddently changed which enhances the electric field in the sheath region causing particles to be ejected from the surface similar to an electron being swept back into the bulk plasma by an ordinary plasma sheath
- The quickness of the fall time (the PACE power supply is under 10 μs) during this portion of the pulse is critical due to ions being drawn to the surface which would neutralize the charged particles. However, as soon as a particle is removed from the surface (due to a short fall time), it's charge prevents it from being redeposited.

Particle Removal Theory

Particles are removed by:

$$F_{repulsive} = q_p E_{matrix}$$

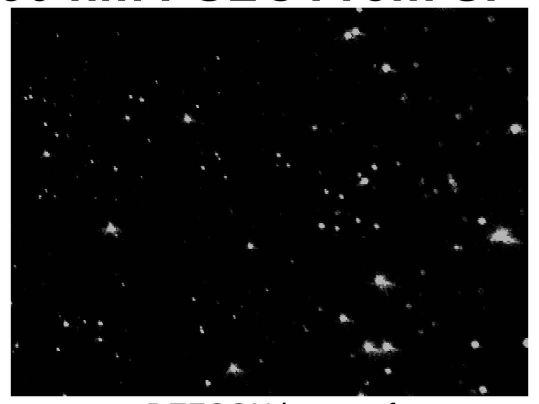
As shown below, the theoretical removal force is greater than the theoretical adhesion force!

Particle Radius [nm]	Theoretical F_{VDW} [N]	"Max" Charge [C]	Number of Excess Electrons	Charging Time [s]	Theoretical Removal Force [N]
30	$2.08x10^{-11}$	$-2.8x10^{-17}$	175	$1.7x10^{-3}$	$3.2x10^{-11}$
80	$5.54x10^{-11}$	$-7.6x10^{-17}$	475	$1.6x10^{-4}$	8.8×10^{-11}
220	$1.52x10^{-10}$	$-2.1x10^{-16}$	1313	$6.0x10^{-5}$	$2.4x10^{-10}$

$$\vec{F}_{VDW} \propto Particle\ Radius \qquad \vec{F}_{Pace\ Removal} \propto Particle\ Radius$$

Removal Results of 30 nm PSL's From Si

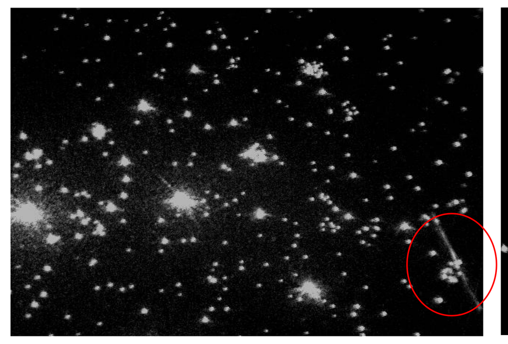
DEFCON image before



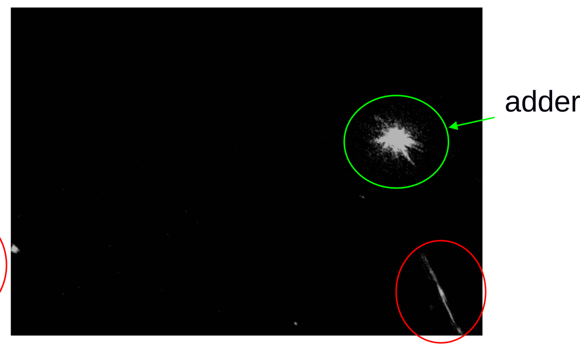
DEFCON image after

These 30 nm PSL's were deposited by an outside source on a 1 inch silicon wafer. The sample was processed in the PACE chamber using optimized plasma and pulsing parameters. **PRE = 96%**

Removal Results of 80 nm PSL's From Si



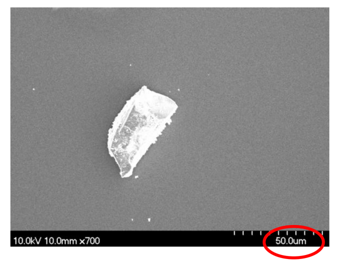
DEFCON image before

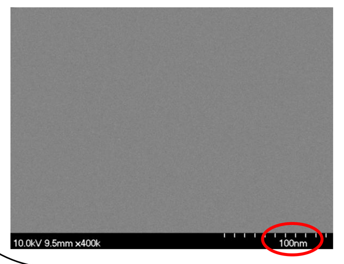


DEFCON image after

These 80 nm PSL particles were deposited at UIUC on a 2 inch silicon wafer. The sample was processed in the PACE chamber using optimized plasma and pulsing parameters. **PRE = 95%**

SEM Inspection of 80 nm PSL Cleaning Results



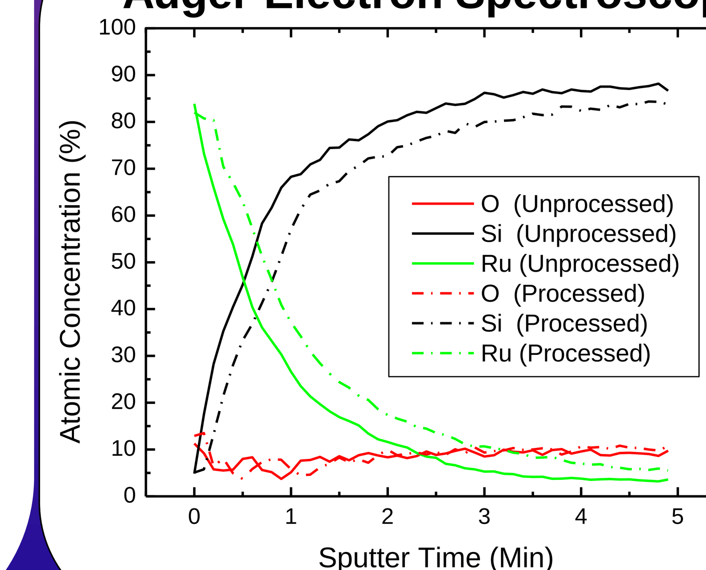


- The top left image is the result of 10 minutes of scanning across the wafer to find some DUST particle to focus on at the 50 micron scale.
- Then the magnification was slowly turned up.
- No other particles (dust or PSL) found on the wafer even at the 100 nm scale.

For the 30 nm PSL removal, the initial density of particles on the surface scattered so much light the field of view was completely covered. These particles were deposited as single particles as well as clumps.

Damage Mitigation Analysis

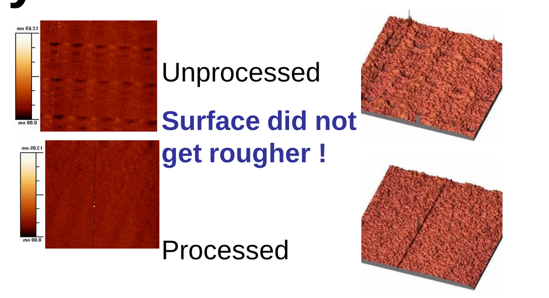
Auger Electron Spectroscopy



Ru still present ! No sputtering seen !

- To confirm the lack of sputtering, auger electron spectroscopy was conducted on a sample exposed to the PACE process.
- The two profiles are almost the same ~ 2.5 nm Ru is still on the top surface.
- Considering there is only 2.5 nm of Ru, seeing the Ru signal is encouraging and shows we did not remove the thin Ru capping layer

Atomic Force Microscopy



Position	RMS Roughness [nm]	
	Unprocessed	Processed
0	0.490	0.521
1	0.525	0.536
2	0.528	0.435
3	1.272	0.436
4	0.897	0.379
Average	**0.742**	**0.461**

The RMS roughness (5 μm by 5 μm) of the processed sample is clearly smaller than the unprocessed sample. However, there are a few islands on the surface as seen in the 3-D pictures, which might possibly be dust on the unprocessed sample. The actual film surface of the processed sample became smoother than the unprocessed sample, which indicates that we cleaned the dust off of the surface while processing these samples using the PACE technique.

Sample Stays Smooth !

Conclusions

The PACE technique for particle removal is effective at removing 30 nm, 80 nm, and 220 nm particles from both ruthenium surfaces as well as silicon surfaces. Future work will continue on the removal of Al_2O_3, SiO_2, Si_3N_4, and other particles from a variety of surface types.

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